

Azimuth Quadrupole Systematics in Au-Au Collisions

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Abstract. We have measured p_t -dependent two-particle number correlations on azimuth and pseudorapidity for eleven centralities of $\sqrt{s_{NN}} = 62$ and 200 GeV Au-Au collisions at STAR. 2D fits to these angular correlations isolate the azimuth quadrupole amplitude, denoted $2v_2^2\{2D\}(p_t)$, from localized same-side correlations. Event-plane $v_2(p_t)$ measurements within the STAR TPC acceptance can be expressed as a sum of the azimuth quadrupole and the quadrupole component of the same-side peak. $v_2\{2D\}(p_t)$ can be transformed to reveal quadrupole p_t spectra which are approximately described by a fixed transverse boost and universal Lévy form nearly independent of centrality. A parametrization of $v_2\{2D\}(p_t)$ can be factored into centrality and p_t -dependent pieces with a simple p_t dependence above 0.75 GeV/c. Results from STAR are compared to published data and model predictions.

1. Introduction

The collective behavior of particles produced in heavy-ion collisions is one of the major topics of study at RHIC, and a large quadrupole component in the distribution on azimuthal angle ϕ has been observed [1]. The large quadrupole azimuthal distribution in non-central collisions is usually described by elliptic flow, in which the different pressure gradients in and out of plane turn the initial position-space anisotropy of the colliding nuclei into a momentum-space anisotropy [2].

The azimuthal anisotropy is typically measured with the quantity v_2 , the second Fourier component of the distribution of particle emission on azimuth with respect to the angle of the reaction plane [3]. In real events this reaction plane angle is not known so many methods exist to estimate v_2 . The present analysis uses a method based on fitting two-dimensional angular correlations similar to [4] but expanded to include the dependence on transverse momentum as well as centrality. A simultaneous analysis of centrality and transverse momentum dependence of v_2 in the absence of “nonflow” from the same-side 2D peak (jet-like correlations) is presented.

One method of measuring v_2 is the event-plane method, $v_2\{\text{EP}\}$, in which particles in the region of interest are used to estimate the reaction plane [3]. A related approach, $v_2\{2\}$, calculates v_2 directly from two-particle correlations [5]. These two methods are essentially equivalent ($v_2\{\text{EP}\} \sim v_2\{2\}$ to 5%) [6]. This analysis, denoted by $v_2\{2D\}$, uses an approach similar to $v_2\{2\}$ but includes the dependence of the two-particle distribution on pseudorapidity as well as azimuth. Significant jet-like correlations are observed at all centralities [7, 8] and their 2D angular dependence can be used to distinguish them from the azimuth quadrupole component, which within the STAR TPC acceptance has no significant η dependence [9]. Jet-like correlations are separated from $v_2\{2D\}$ by 2D model fits described in Sec. 3.

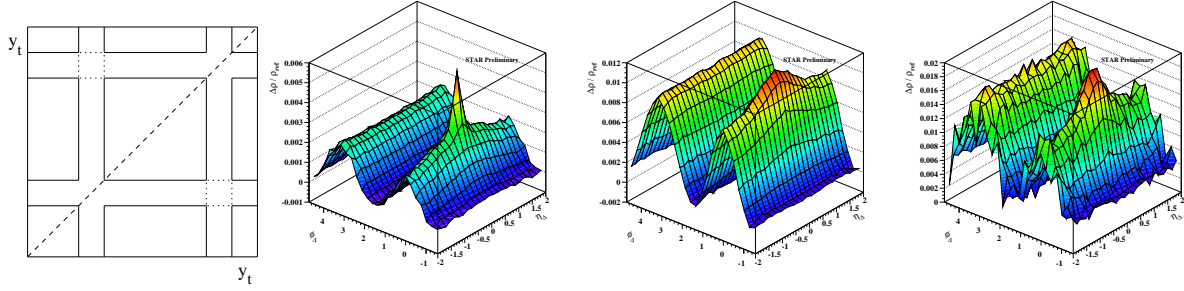


Figure 1. Left Panel: Two examples of marginal distribution cuts in $y_t \times y_t$ space. Remaining panels: An example of the y_t evolution of correlation structures for 40-50% central collisions. The plots correspond to y_t bins of $1.4 < y_t < 1.8$, $3.0 < y_t < 3.4$, and $3.8 < y_t < 4.2$.

2. Correlations

Angular correlations without a trigger particle are constructed by considering all pairs of particles in an event. For each particle the azimuth angle ϕ , pseudorapidity η and transverse momentum p_t are measured, defining a six dimensional two-particle space. Integrating over p_t and projecting the angular variables onto their difference axes $\eta_\Delta \equiv \eta_1 - \eta_2$ and $\phi_\Delta \equiv \phi_1 - \phi_2$ yields 2D angular autocorrelations [4, 7, 10].

The correlation measure is constructed from pair densities. Sibling pairs from the same event contain the primary signal. Mixed pairs from different events are useful as a reference for removing detector artifacts. The basic correlation measure we use is $\Delta\rho/\rho_{ref}$, the ratio of the sibling minus the mixed pairs to the mixed pairs, a per-pair measure. It is also sometimes desirable to use a two-particle measure like $\Delta\rho/\sqrt{\rho_{ref}}$ [11]. However, this analysis uses $\Delta\rho/\rho_{ref}$ which is easily converted to v_2 : $2v_2^2\{2D\} \equiv \Delta\rho[2]/\rho_{ref}$, where the [2] indicates the quadrupole term of the fit model in Eq. 1 below.

When we consider momentum dependence it is desirable to use transverse rapidity instead of transverse momentum: $y_t = \ln\{(p_t + m_t)/m_0\}$. Transverse rapidity is the analogue to longitudinal rapidity but in the transverse direction. For unidentified particles we make the approximation $m_0 = m_\pi$ to define a regularized $\ln(p_t)$ measure.

We construct marginal distributions by restricting the y_t range of one of the particles in the two-particle correlation to a certain interval. Due to the inherent diagonal symmetry in $y_t \times y_t$ space this corresponds to making cross-shaped cuts as seen in Fig. 1 (left panel). These cuts are analogous to the procedure in a standard event-plane $v_2(p_t)$ analysis [3] in which particles from the full momentum range are used to estimate the event plane and particles in the momentum interval are correlated to it. The marginal distributions allow us to study correlations at large p_t values and are easily converted into the usual $v_2(p_t)$ measure for comparison with published $v_2(p_t)$ data.

In this analysis there is a minimum p_t cut for all particles of 150 MeV/c which corresponds to a pion y_t of 0.93. There are nine y_t bins. The first y_t bin includes all particles with y_t less than 1.4 and the seven subsequent bins are 0.4 units of y_t wide. The final bin includes all particles with y_t greater than 4.2. This corresponds to particles above ~ 5 GeV/c.

3. Fit Parameters

This analysis is based on 14.5 million Au-Au collisions at $\sqrt{s_{NN}} = 200$ GeV and 6.7 million Au-Au collisions at $\sqrt{s_{NN}} = 62$ GeV observed with the STAR TPC. The acceptance was defined by transverse momentum $p_t > 0.15$ GeV/c, $|\eta| < 1$ and 2π azimuth. Minimum-bias event samples were divided into 11 centrality bins: nine $\sim 10\%$ bins from near 100% to 10%,

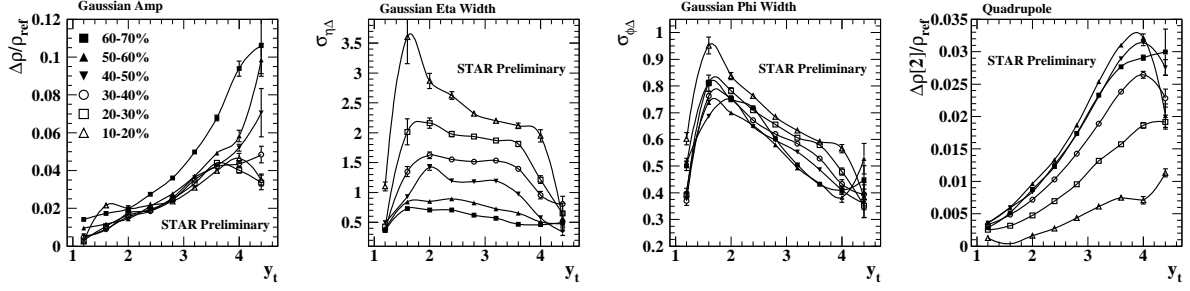


Figure 2. The amplitude, width in η_Δ , and width in ϕ_Δ of the 2D Gaussian and the amplitude of the quadrupole component of the fit for Au-Au 200 GeV 60-70%, 50-60%, 40-50%, 30-40%, 20-30%, and 10-20% collisions. Error bars are for fit errors only.

the last 10% divided into two $\sim 5\%$ bins.

Two-particle correlation histograms are constructed for each of the 11 centrality and 9 y_t bins described above for a total of 99 bins at each $\sqrt{s_{NN}}$. Example histograms are shown in Fig. 1. Fig. 2 shows the evolution of the most relevant fit parameters at $\sqrt{s_{NN}} = 200$ GeV with y_t for six centrality bins. Systematics errors are still under study. 62 GeV results have similar trends as 200 GeV.

In order to distinguish the quadrupole signal from η -localized (jet-like) correlations we will fit the major structures in the 2D histograms. The fitting model used is similar to that used in [4], but the sharp peak from electron pairs is excluded rather than fit. The histograms are constructed with 24 bins on ϕ_Δ with centers ranging from $-\pi/2$ to $17\pi/12$ in steps of $\pi/12$ and 25 bins on η_Δ with centers ranging from -1.92 to 1.92 . A total of seven bins are excluded from the fit, where $\eta_\Delta = 0$ and $\phi_\Delta = 0, \pm\pi/12$ and where $\phi_\Delta = 0$ and $\eta_\Delta = \pm 0.08, \pm 0.16$.

The complete fitting function is then

$$F = A_{\phi_\Delta} \cos(\phi_\Delta) + A_{2\phi_\Delta} \cos(2\phi_\Delta) + A_0 e^{-\frac{1}{2} \left(\frac{\eta_\Delta}{\sigma_0} \right)^2} + A_1 e^{-\frac{1}{2} \left\{ \left(\frac{\phi_\Delta}{\sigma_{\phi_\Delta}} \right)^2 + \left(\frac{\eta_\Delta}{\sigma_{\eta_\Delta}} \right)^2 \right\}} + A_2. \quad (1)$$

There are 5 terms and 8 parameters. Two of the terms are sinusoids on ϕ_Δ , one is a constant offset, and one models only structure on η_Δ . Thus, the remaining term—the two-dimensional Gaussian—is solely responsible for describing “nonflow” [6].

Fig. 3 (first three panels) shows measured quadrupole results from this analysis vs. p_t compared to previously published $v_2\{EP\}$ results for 30-40%, 5-10% and 0-5% central collisions. In the case of 0-5% the quadrupole component was found to be too small to measure reliably so the cross-hatched region represents an upper bound. We calculate the contribution of the 2D Gaussian peak to the second Fourier component using the measured amplitudes and widths in the curve labeled ‘jets’. We find $v_2\{EP\}$ seems to be dominated by the SS peak structure in 5-10% collisions and entirely due to it in 0-5% collisions. This has important implications for the interpretation of published v_2 data.

4. Quadrupole Descriptions

Consider a model in which the single-particle density on y_t and ϕ and corresponding transverse boosts can be decomposed into azimuth-independent ρ_0 and quadrupole ρ_2 pieces [12]. Define $V_2(y_t, b) \equiv \rho_0(y_t, b)v_2(y_t, b)$ and invoke a blastwave model to get the relation $V_2(y_t, b) \approx p_t \Delta y_{t2}(b) \rho_2(y_t, b) / (2T_2)$ where Δy_{t2} is the quadrupole component of the radial boost distribution, ρ_2 is the quadrupole spectrum, and T_2 is a blastwave parameter. Now construct the unit-integral quantity $Q(y_t, b) \equiv [V_2(y_t, b)/p_t] / [V_2(b) \langle 1/p_t \rangle] \approx [\rho_2(y_t, b)] / [\rho_2(b)]$. Most of the parameters drop out and this variable directly relates measurable quantities to the quadrupole spectrum model.

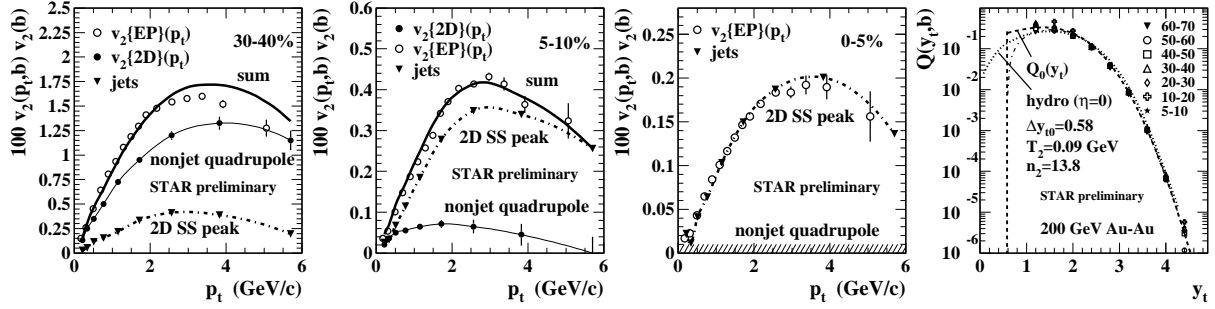


Figure 3. First three panels: Comparison of published $v_2\{EP\}$ for Au-Au 200 GeV 30-40%, 5-10% and 0-5% central collisions [9] and results from this analysis. Errors are fit errors only. Right Panel: The quadrupole spectrum data $Q(y_t, b)$ and fit $Q_0(y_t)$. The dotted curve is a zero-viscosity limit of a viscous hydro theory defined in [13].

There is little centrality dependence to the quantity $Q(y_t, b)$. A single Lévy distribution $Q_0(y_t)$ can describe the data within 10% with a few simple parameters: a y_t boost $\Delta y_{t0} = 0.58$ and parameters $T_2 = 0.09$ GeV and $n_2 = 13.8$. There is deviation from this curve for very central collisions at low- p_t . A similar analysis was made in [12] for minimum-bias identified particles without centrality dependence and the observed boost values agree. It is notable that the boost is a single sharp value and not a distribution as would be expected from transverse Hubble expansion.

A related and more accurate parametrization has been made. At higher p_t it is observed that $v_2\{2D\}(p_t, b)$ is proportional to $p_t \exp(-p_t/4)$ so we derive the form:

$$v_2\{2D\}(p_t, b) \approx \langle 1/p_t \rangle v_2\{2D\}(b) p_t \exp(-p_t/4) \times f(p_t, b), \quad (2)$$

where $\langle 1/p_t \rangle \approx 2.1$ (GeV/c) $^{-1}$ and $f(p_t, b)$ is a dimensionless factor necessary for the full p_t and centrality dependence. It is fit to data to get $f(p_t, b) = 1 + C(b)[\text{erf}(y_t - 1.2) - \text{erf}(1.8 - 1.2)]$ and $C(b) = 0.12 - (\nu - 3.4)/5 - [(\nu - 3.4)/2]^5$.

Using 2D correlations we observe $v_2(p_t)$ for a wide range of centralities without significant “nonflow” contamination and conclude that published $v_2(p_t, b)\{EP\}$ results [9] contain a significant contribution from the same-side peak correlations.

We have measured the quadrupole on y_t as a function of b and deduced the quadrupole spectrum variation with centrality. This is the first complete factorization of the scaling properties of the quadrupole. A detailed study of the systematics is in progress. When the quadrupole spectrum is isolated we also observe a single b -independent y_t boost value that is consistent with the minimum-bias results for different particle species [12]. We developed an accurate parametrization of $v_2\{2D\}$ over a large kinetic domain and surprisingly simple trends are observed.

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